

## Oscillations of the Critical Temperature in a (Fe/Cr/Fe)/V/Fe Heterostructure

V. A. Tumanov<sup>a, \*</sup>, Yu. V. Goryunov<sup>b</sup>, and Yu. N. Proshin<sup>a</sup>

<sup>a</sup> Kazan Federal University, Kazan, 420008 Russia

<sup>b</sup> Zavoisky Physical-Technical Institute, FRC Kazan Scientific Center, Russian Academy of Sciences, Kazan, 420029 Russia

\*e-mail: tumanvadim@yandex.ru

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The superconducting and magnetic properties of the (Fe/Cr/Fe)/V/Fe layered system with variable thickness of the chromium layer have been experimentally and theoretically studied. The magnetic properties of the system have been studied by the ferromagnetic resonance method, and the superconducting transition temperature has been measured from the jump in the magnetic susceptibility. A wide variety of magnetic states are observed in the system; in particular, the structure of small domains can arise in the iron layer placed between vanadium and chromium. It has been shown experimentally that the critical temperature  $T_c$  of the superconducting transition undergoes nonmonotonic oscillations with a noticeable amplitude in the given system with the change in the thickness of the Cr layer. The proposed model based on the proximity effect theory makes it possible to relate these  $T_c$  oscillations to the features of the magnetic structure of the samples.

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The coexistence of superconductivity and ferromagnetism within a uniform sample requires specific conditions, which are difficult to fulfill. It can be achieved in superconductor–ferromagnet heterostructures either by spatial separation of ferromagnetic and superconducting materials (the proximity effect) or by the suppression of the effective exchange field. The spatial separation makes it possible to combine magnetic and superconducting properties within a single sample because of the large delocalization of Cooper pairs, which transfer superconducting correlations in the near-boundary layer of a ferromagnet. The emerging competition of superconductivity and magnetism leads to the appearance of a number of interesting effects, in particular, a nonmonotonic dependence of the critical temperature and Josephson current on the thicknesses of the ferromagnetic layers  $d_f$  (see reviews [1–4] and references therein). Magnetic inhomogeneities of various nature (domain walls, helical magnetic structures, artificially created multilayer structures with different directions of magnetization) in the ferromagnetic layer significantly complicate the structure of superconducting correlations in the superconductor–ferromagnet system. The directionally inhomogeneous magnetization within the ferromagnetic layer leads to the appearance of triplet superconducting correlations with a nonzero spin projection [5–7] and affects the critical temperature of the superconducting transition. Theoretical estimates of this effect were carried out, e.g., in [8, 9].

In this work, we study the magnetic and superconducting properties of a system where it is possible to form domains whose dimensions are about the superconducting coherence length. The experimental implementation of such a system is the contact of a superconductor with a magnetic system (Fe/Cr/Fe), which in itself is of great interest [10, 11]. In the (Fe/Cr/Fe) system, the phenomenon of giant magnetoresistance is observed [12], while the mutual orientation of the magnetizations of the iron layers as a function of the thickness of the chromium layer is very complex and depends on the conditions for the deposition of the layers [10].

For the studies, two series of samples were prepared on a single-crystal MgO (001) substrate. The first series of Fe/V(335 Å)/Fe samples include symmetric wedge-shaped iron layers, where the top layer is protected by Pd (20 Å). The second series of Fe (8 Å)/Cr/Fe (8 Å)/V (340 Å)/Fe (20 Å) samples have a wedge-shaped chromium layer, where the upper layer is protected by vanadium (60 Å). Here and below, the layers are listed from left to right in the order of deposition. During the deposition, the temperature of the substrates was 300°C, which is optimal for obtaining the smoothest layers and, correspondingly, sharp interfaces [10, 13, 14]. The process of obtaining samples is described in detail in [14, 15]. We note that an iron layer 8 Å thick in the Fe/Cr/Fe magnetic system corresponds to 5.5 monolayers. At this thickness, the upper iron monolayer in the first layer is half com-